WILLOW GROVE, RAINBOW AND PIGICK: THREE NEW METEORITE FINDS IN VICTORIA, AUSTRALIA

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Three new and distinctive meteorites have recently been discovered by chance during ploughing activities in Victoria. The Rainbow and Pigick meteorites were found together near Rainbow in the Mallee region, and the Willow Grove meteorite in the Latrobe Valley. Rainbow, consisting of two stones totalling 1.55 kg, shows characteristics of the rare class CO3 carbonaceous chondrites. Pigick, consisting of eight stones totalling about 600 g, is an H5 ordinary chondrite showing weak to moderate shock features. Willow Grove, made up of two masses of 9 and 2.7 kg, is an anomalous ungrouped ataxite with one of the highest known nickel contents (average 28%). It has a unique structure consisting almost entirely of lath martensite, formed by shear transformation of high temperature austenite with no apparent kamacite.

Key words: Rainbow meteorite, CO3 carbonaceous chondrite, Pigick meteorite, shocked features, Willow Grove meteorite, Ni-rich ataxite, plate martensite, Victoria.

FROM time to time, farmers in the more arid parts of Victoria by chance discover meteorites (eg. the Turriff meteorite from the Mallee region (Birch 1999). Two recent finds are from near the small town of Rainbow, in the Wimmera region. A total of ten fragments (Table 1; Fig. 1) were found in 1994 by Darryl Wedding while he was ploughing wheat paddocks about 12 km west of the town. Eight of these fragments, totalling 690 g, represent a single H5 ordinary chondrite, and have been named Pigick, after the local parish. The other two pieces, with a total weight of 1.55 kg, are of a rare carbonaceous chondrite (type CO3), which has been named Rainbow, after the nearest town. Both pieces of Rainbow and four fragments of Pigick (~ 360 g) were donated to Museum Victoria by the finder.

The third recent meteorite discovery was not in semi-arid Victoria, but in the much wetter Latrobe Valley, in the south-east of the State. David Buckley ploughed up two pieces (Fig.2) of an iron meteorite, totalling 11.7 kg, on his farm near the township of Willow Grove, 110 km ESE of Melbourne. The smaller piece (2.7 kg) was discovered in 1995, the larger (9 kg) in 1998. The meteorite has been classified as an ungrouped Ni-rich ataxite and named Willow Grove, after the nearest town. The larger piece was retained by the finder, but the smaller was donated to Museum Victoria.

All three meteorite names have been approved by the Nomenclature Committee of the Meteoritical Society. Both Willow Grove and Rainbow are highly unusual meteorites and are currently being investigated in more detail (Grossman et al. 2000; Scorzelli et al. 2000; Birch et al. 2001).

	MV Cat. No.	Dimensions (mm)	Mass (g)
Rainbow	E15238	135 × 90 × 65	1132
	E15237	95 × 70 × 45	421
Pigick	E15239	80 × 55 × 40	169
		65 × 50 × 30	156
		not measured	*c.* 110
	E15241	55 × 40 × 30	103
	E15242	65 × 35 × 25	63
		48 × 45 × 25	58
	E15240	35 × 25 × 15	26
		35 × 20 × 10	8

Table 1. Approximate mass and size for the pieces of the Rainbow and Pigick meteorites. Specimens without MV numbers are held by the finder. E15241 has been reduced to 80 g during investigation.

Fig. 1. (a) Rainbow meteorite (two large stones at rear) and Pigick meteorite (smaller stones). The Pigick stone at centre-front was polished by the finder. The larger Rainbow stone is 135 mm long. (b) The second largest Rainbow stone showing pale-colored chondrules on the weathered surface (stone is 95 mm long).

Fig. 2. The Willow Grove meteorites. (a) 2.7 kg mass (100 × 70 × 70 mm). (b) 9 kg mass (160 × 160 × 110 mm).

THE RAINBOW METEORITE

Location

The two pieces of the Rainbow meteorite were found in allotment 8, Parish of Pigick, about 1 km apart, along an approximate E–W line (Fig. 3). The geographic coordinates are approximately 35°54.4′S.141°51.3′E. The site is sandy soil derived from the Cainozoic sediments of the Murray Basin; no hard rock outcrops are known in the region.

Appearance and mineralogy

The two stones weighed 1.132 kg and 421 g when discovered, with dimensions 135 × 90 × 65 mm and 95 × 70 × 45 mm, respectively. They appear highly weathered, with a smooth, dark brown exterior surface, on which abundant chondrules can be made out under the microscope. Some irregular films of reddish brown iron oxide, with small embedded quartz grains derived from the surrounding soil, may represent original fusion crust.

In thin section, iron oxide veining is common and silicate minerals are heavily stained. Chondrules are distinct and abundant, almost all less than 0.5 mm across, with most less than 0.2 mm (Fig. 4). They are set in a very fine-grained, near opaque matrix. The most common type of chondrule contains porphyritic olivine and orthopyroxene, but others consisting of cryptocrystalline and barred olivine and porphyritic olivine are also present. Olivine compositions obtained by electron microprobe analysis are markedly heterogeneous, ranging from Fa_{45} to $Fa_{0.2}$. There is a broad peak between Fa_0 and Fa_7 (Fig. 5). Many low-FeO olivines have extremely high CaO contents, exceeding 0.4 wt. %. Grains of orthopyroxene are also present. They are low in FeO, with compositions in the range $Fs_{0.5-7.4}Wo_{0.4-4.6}$, averaging $Fs_{3.4}Wo_{1.6}$. Other minerals detected included rare Ca-rich plagioclase in the groundmass and uncommon tiny grains of kamacite (4.8–14.4% Ni; 0.27–1.2% Co), taenite (43.1% Ni) and troilite.

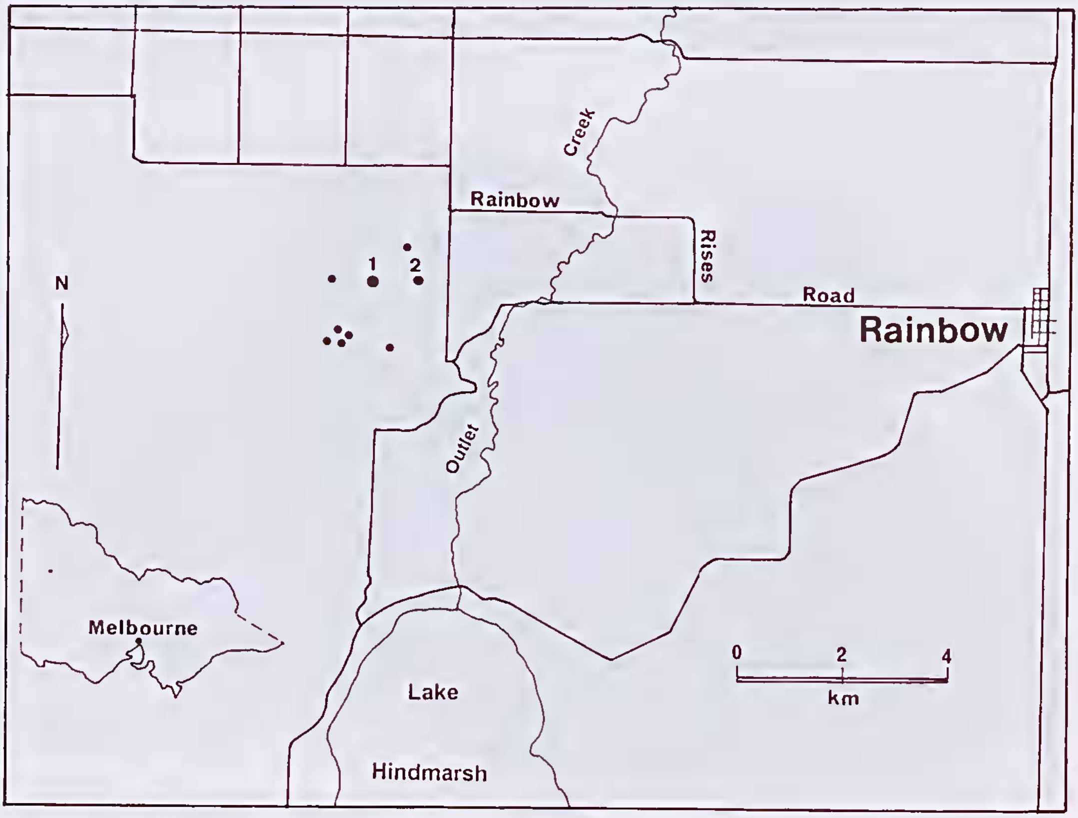

Fig. 3. Locality map for the Rainbow (1 and 2) and Pigick meteorites.

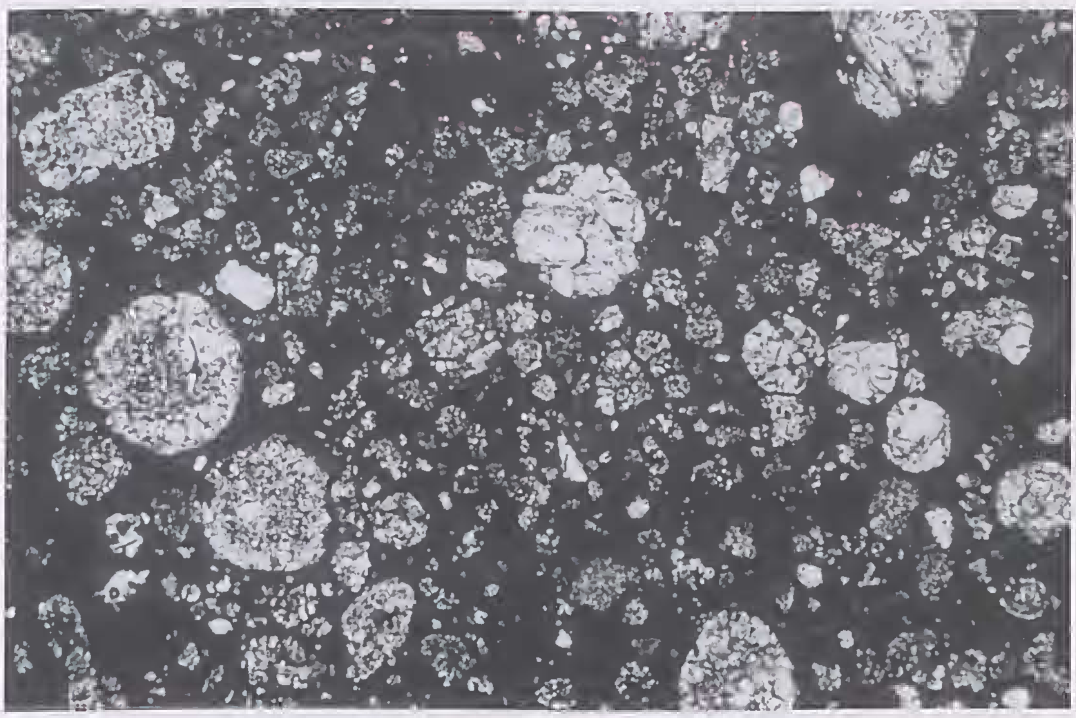

Fig. 4. Thin section of Rainbow showing typical chondrules (largest is 0.45 mm across).

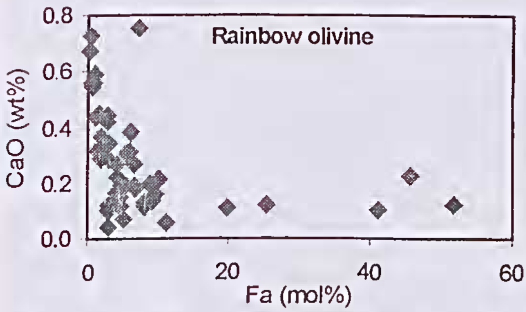

Fig. 5. Olivine compositions in Rainbow (from Grossman et al. 2000).

The presence of amoeboid olivine inclusions (AOIs) and fine-grained calcium–aluminium inclusions (CAIs) was also noted (Grossman et al. 2000). The AOIs contain thin veins (0.4–0.8 μm) of olivine (~ Fa_8) crosscutting larger crystals of forsterite ($Fa_{1.8}$). Small irregular grains of anorthite and diopside are dispersed through the AOIs.

The mineralogy of the meteorite strongly resembles that of the rare CO3 class of carbonaceous chondrites. Only about 20–25 distinct CO3 meteorites are known, with Rainbow being the seventh from outside Antarctica and the Sahara.

Thermoluminescence and O-isotopes

Additional techniques have been used to classify the Rainbow meteorite. These are reported in more detail by Grossman et al. (2000). On a scale from 3.0 to 3.7, CO3 meteorites show increasing metamorphism (Brearley & Jones 1998). Thermoluminescence properties for Rainbow are similar to those shown by Type 3.1–3.2 chondrites, although it is likely that the TL sensitivity of Rainbow reflects terrestrial weathering in addition to parent-body metamorphism. Oxygen isotope analysis shows that Rainbow has a heavier O-isotopic composition than any previously measured CO3 chondrite, but the data fall on the regression line passing through other CO3s (Fig. 6). Previously it has been argued that there was a rough correlation between O-isotopic composition and metamorphic grade for CO3 chondrites (Rubin 1997). However, if Rainbow is subtype 3.1–3.2, as implied by its mineralogy and TL properties, then its O-isotopic composition plots well away from other CO3s of similar metamorphic grade and this correlation is destroyed.

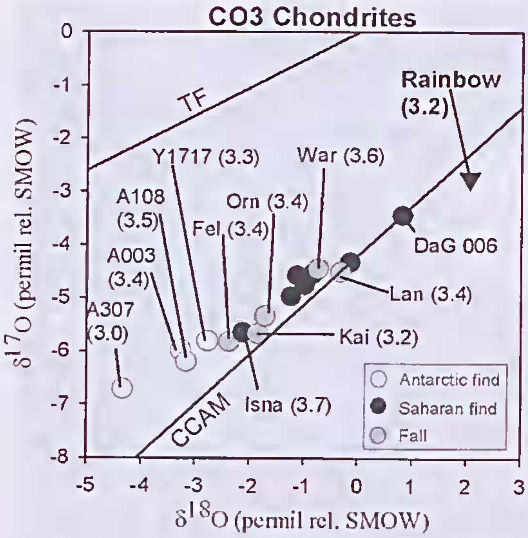

Fig. 6. O-isotopes for Rainbow and other CO3 meteorites (modified slightly from Grossman et al. 2000). *Abbreviations:* TF = terrestrial fractionation line; CCAM = carbonaceous chondrite anhydrous minerals mixing line; SMOV = standard mean ocean water; A003 = Allan Hills (ALH) A77003; A108 = ALH83108; A307 = ALHA77307; DaG006 = Dar al Gani 006; Fel = Felix; Kai = Kainsaz; Lan = Lancé, Orn = Ornans, War = Warrenton; Y1717 = Yamato 791717. Unlabelled Saharan meteorites include Acfer 202 and 243, Dar el Gani 023 and 025, and Hammadah al Hamra 043.

Weathering features shown by Rainbow, such as the prominent iron staining and the almost complete loss of metals and sulphides, indicate it is about W3 on the weathering scale (Wlotzka 1993). Such weathering under the hot dry conditions of the Victorian Mallee may have slightly enriched the heavy O isotopes but probably not sufficiently to maintain the link between isotopic composition and metamorphic grade (Grossman et al. 2000). Based on the evidence to date, the closest CO3 chondrite to Rainbow appears to be Kainsaz (CO3.2), which was seen to fall near Muslyumov, Russia, in 1937 (Grossman et al. 2000).

THE PIGICK METEORITE

Location

Fragments of the meteorite were found scattered randomly in allotments 7A and 8, Parish of Pigick (Fig. 3), with the same geographic coordinates as the Rainbow meteorite. The two larger pieces were found apart from a cluster of the smaller pieces. This distribution suggests there are more stones undiscovered.

Appearance and mineralogy

Like Rainbow, the fragments of the Pigick meteorite are highly weathered in appearance, with a thin limonitic outer crust in which are embedded small quartz grains derived from the surrounding soil. The pieces, with weights ranging from 169 g down to 7.6 g, are irregular in outline and crossed by deeply penetrating cracks (Fig. 1). Despite this weathering, the internal structure is coherent and small grains of bright metallic minerals are visible on polished surfaces.

In thin section, chondrules are reasonably common but usually quite indistinct due to strong recrystallisation. The most obvious chondrules are barred varieties containing olivine, orthopyroxene and plagioclase. They range between about 0.5 and 2 mm across and are set in a recrystallised, highly fractured matrix. The fractures show strong sub-parallel alignment and are filled with iron oxides, which also stain grain boundaries (Fig. 7). These features make it difficult to distinguish between coarser-grained chondrules, individual silicate fragments and coarse grains in the recrystallised matrix. On the weathering scale of Wlotzka (1993), Pigick rates about W3. This is similar to Rainbow, but in the absence of absolute dating no direct conclusion can be drawn from this observation.

Marked undulose extinction is a feature of the larger silicate grains and there is limited development of planar fractures in olivine grains (Fig. 8). These features suggest a level of S3 on the scale of shock metamorphism (Stöffler et al. 1991).

Limited electron microprobe data showed that orthopyroxene compositions are homogeneous, averaging $En_{81.9}Fs_{16.6}Wo_{1.5}$. The CaO contents in the orthopyroxenes are typical of Type 5 chondrites (Scott et al. 1986). Olivine compositions are also quite homogeneous, averaging $Fo_{80.8}Fa_{18.8}Te_{0.4}$. The values of Fa in olivine and Fs in orthopyroxene clearly fall within the field of H chondrites (Brearley & Jones 1998). Clinopyroxene was not detected. The feldspar occurring in chondrules and as a minor matrix component is oligoclase (average $Ab_{78}An_{13}Or_{9}$). Of the metallic minerals, troilite is the most abundant, forming irregular grains up to 0.4 mm across. It is relatively lightly affected by alteration to goethite, unlike the slightly smaller kamacite and taenite grains, which in many places occur as relicts in patches of goethite. The few analyses obtained indicate a range of 35.4–46.9% Ni in taenite and 3.8–6.7% Ni in kamacite.

Fig. 7. Highly fractured texture in the Pigick meteorite. Note the pervasive system of sub-parallel fractures (field of view 3 mm across).

Fig. 8. Shock features in the Pigick meteorite. The large olivine grain shows undulose extinction and there are also poorly developed planar fractures, for example in grain to lower left (field of view 1.2 mm across).

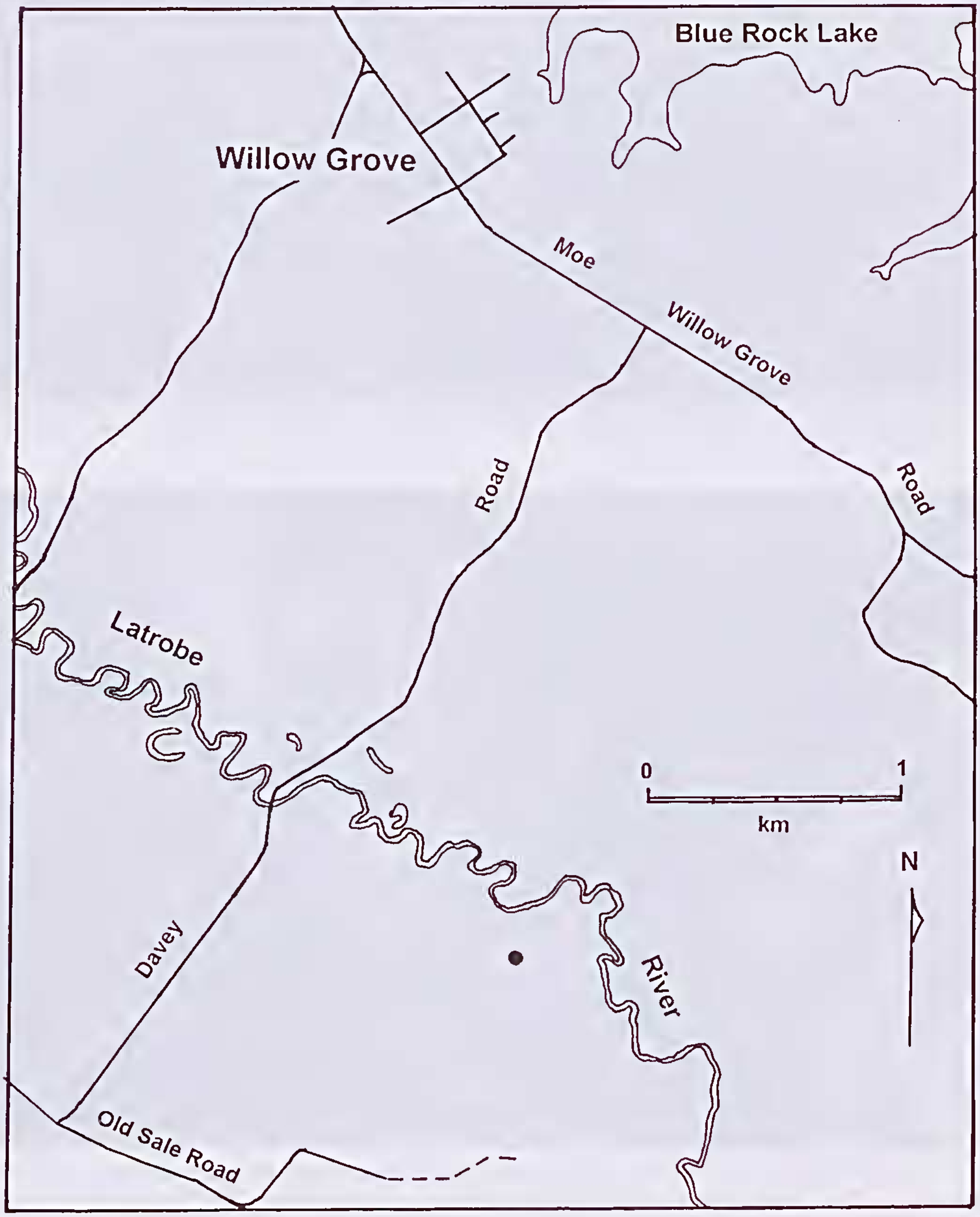

Fig. 9. Locality map for the Willow Grove meteorite.

No bulk chemical data have been obtained on the Pigick meteorite. Nevertheless the mineralogical features and compositions strongly suggest it is an H5 ordinary chondrite showing weak to moderate shock features. Dimboola is the only other H5 meteorite from Victoria, but does not show shock features (Mason 1974).

THE WILLOW GROVE METEORITE

Location

The two pieces of the Willow Grove iron meteorite were found within metres of each other in a paddock on the Buckley farm, off Old Sale Road, between Westbury and Willow Grove (Fig. 9). The site is near the top of the north-west flank of a small knoll overlooking the Latrobe River and has approximate geographic coordinates of 38°6.2′S,146°10.9′E. The high point is capped by a Tertiary conglomerate shedding rounded pebbles of reef quartz and chert into the soil.

Appearance, mineralogy and structure

Both masses are irregular lumps with a thin, dark brown oxidised coating, with no recognisable 'thumb-prints'. The smaller mass is roughly five-sided, measuring approximately 100 × 70 × 70 mm. The larger piece, measuring 160 × 160 × 110 mm, consists of two roughly ovoid masses joined along a neck which may be an incipient fracture. The two masses cannot be fitted together, even allowing for removal of surfaces by oxidation. Bright metal is easily exposed beneath the oxide crust, which X-ray diffraction revealed consists of a mixture of maghemite and reevesite (nickel carbonate), with minor goethite. There are thin scour marks made by the plough on both pieces. Pitting and remelting caused by an oxyacetylene flame are present in several places on the smaller mass (Fig. 2).

A portion of the meteorite was prepared for examination of three orthogonal sections under reflected light microscopy. Etching in 10% nital solution revealed on two of the sections a system of closely spaced tabular features identifiable as lath martensite (Fig. 10). Martensite in Fe–Ni alloys is a body-centred cubic phase resulting from the diffusionless shear and twin-related transformation of the high temperature face-centred cubic phase (austenite) during cooling. The tabular features are between 5 and 20 μm across and can be taken to consist of packets of finer martensite crystals (Krauss & Marder 1971) that are not readily observable in reflected light. The arrangement of these lath packets varies considerably. In the simplest structure only one system of packets dominates, but may be crossed by occasional narrow bands containing a secondary system of lath packets. More complex structures are represented by much higher concentrations of these secondary lath systems. Large numbers of microcracks are present through the sections, in particular near the outer surface of the meteorite. These cracks appear to be filled with the same corrosion product as forms the outer crust and have been attributed to stress corrosion (Birch et al. 2001). The only other phase present is schreibersite, occurring as very rare grains.

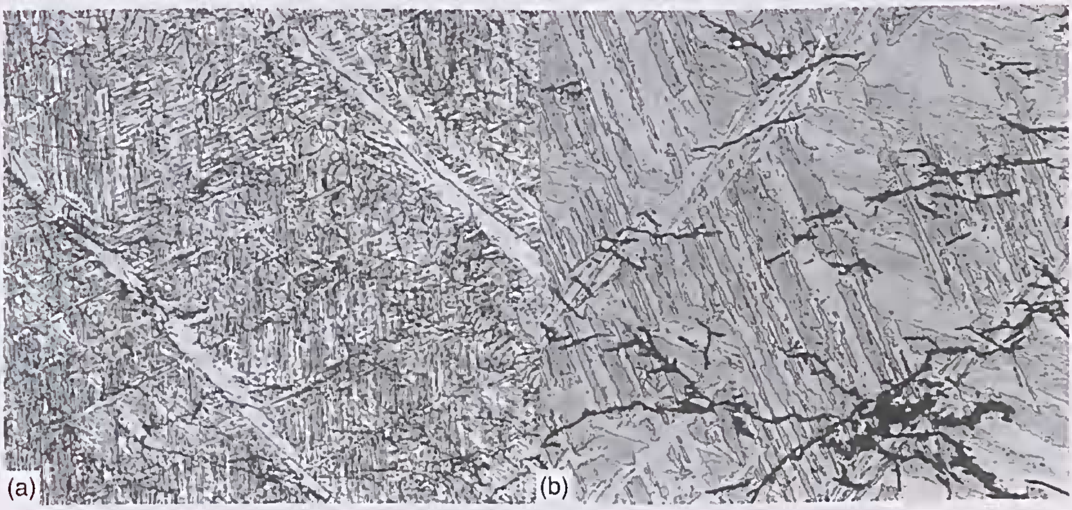

Fig. 10. Typical structures in Willow Grove meteorite. The main feature is lath martensite, forming the plate-like texture, crossed by a network of microcracks [field of view is 1.6 mm across in (a), 0.3 mm across in (b)].

Composition

Chemical analysis by electron microprobe and instrumental neutron activation analysis gave bulk Ni contents between 26.4 and 29.0 wt. %, with an average of 27.9 wt. %. Cobalt contents are between 1.06 and 1.23 wt. %, averaging 1.2 wt. %. The INAA analyses gave similar values for Ni and Co, as well as data for other minor elements such as Ga, As, Ir and Au (see Table 2). Atomic emission spectroscopy showed the carbon content to be 0.15 ± 0.01 wt. % and the phosphorus content to be less than 0.01 wt. %.

Willow Grove has high contents of the refractory elements Re, Ir and Pt, and low contents of the volatile elements Cu, Ga, As and Au. If these are converted to element/Ni ratios, they are much lower than those for any known group of chondritic meteorites. In addition, the W/Ir ratio of Willow Grove is significantly lower than equivalent ratios for metal nodules from ordinary chondrites (Kong et al. 1998).

Comparison with other meteorites

The structure and composition of Willow Grove make it a unique meteorite. Amongst the small number of meteorites with Ni contents between 25 and 35 wt. %, that of Willow Grove is exceeded by Santa Catharina (35%), Tishomingo (32.1%), Twin City (29.9%) and Lime Creek (29.5%). Tishomingo (Buchwald 1975; Ives et al. 1978) and Willow Grove are the only two of these that consist almost entirely of martensite. However, Tishomingo consists of plate martensite (Buchwald 1975), in contrast to the lath martensite of Willow Grove. Studies of laboratory alloys show that martensite generally forms with a lath morphology at low Ni concentrations and with plate morphology at higher Ni concentrations, with the transition occurring in the range 28–30 wt. % (Brofman & Ansell 1982). It therefore appears that the transition in meteorites occurs over a near-identical range of Ni contents, even allowing for the effects of other elements such as Co and C that may affect the transition in opposite ways.

Origin and cooling history

The very low content of volatile elements in Willow Grove, including the low W/Ir ratio, may have been caused by a high-temperature impact in an asteroid setting, that led to out-gassing from a relatively oxidised, possibly chondritic, regolith. On the other hand, depletion in volatile elements could be attributed to inheritance from a chondritic precursor that accreted at very high temperatures (Kelly & Larimer 1977; Scott et al. 1996).

During subsequent cooling, there was enough residual heat to allow the growth of moderately large (> 5 cm) crystals of taenite (= austenite in metallurgical terms). The material continued to cool through the (kamacite + taenite) field to a temperature (the MS temperature) at which the transformation to martensite commenced. Based on an MS temperature of ~ 65°C obtained for a laboratory Fe-27 wt. % Ni alloy austenised at high temperature (Brofman & Ansell 1982), the MS temperature for Willow Grove is likely to have been similar. The absence of kamacite in Willow Grove may be due to the very low schreibersite content, as early-formed schreibersite has been observed to assist the nucleation of kamacite in low-Ni Fe meteorites (Naryan & Goldstein 1984). Alternatively, the cooling rate may have been rapid enough to suppress kamacite nucleation. It is not possible to detect any retained taenite by light microscopy, so it is uncertain whether the transformation to martensite was completed during cooling to the lowest temperature reached in space. Heating accompanying the meteorite's passage through the Earth's atmosphere would not have affected any of the observed features in the interior of the preserved pieces. Once in the weathering environment, the meteorite was subject to stress corrosion by terrestrial fluids, leading to the observed system of microcracks.

CONCLUSIONS

Rainbow and Willow Grove are two highly distinctive and unusual meteorites. They show some properties that are at or beyond the limits

	Cr µg/g	Fe wt.%	Co wt.%	Ni wt.%	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	W µg/g	Re ng/g	Ir µg/g	Pt µg/g	Au µg/g
*		71.0	1.13	27.5									
+	170		1.21	27.9	10	0.23	< 40	0.783	1.52	2550	17.4	23.7	0.233

Table 2. Chemical analysis of the Willow Grove meteorite. *electron microprobe data (Museum Victoria); + INAA data from J. Wasson (UCLA).

shown by their particular types in the meteorite classification scheme, and hence extend our knowledge of asteroid formation. While a common type, Pigick shows shock features that have not been observed in any other Victorian meteorite. The occurrence of these three meteorites in such a relatively restricted part of the Australian continent should encourage further discoveries.

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